Environmental Monitoring By Remote Sensing From Air and Space

WILLIAM O. DAVIS

Deputy Chief of Atmospheric and Space Division
National Oceanic and Atmospheric Administration

People around the world have today become newly aware of the environment, not only as the provider of resources for economic development, but as the basis of life itself, within which man and his children must live for centuries to come, if they are to live at all. There is rising concern all over the world both for the effect of the natural environment on man and his activities and for the rate at which the environment is being degraded with the growth of technology and the progress of economic development. There is genuine fear that environmental quality may not only decline sufficiently to make life unpleasant, but even to the extent that human life may become impossible on the terrestrial globe. In the meantime, growing population densities and increased value of structures and property mean that every new hurricane, earthquake, or other natural disaster potentially takes an increasing toll of human life and economic resources. Thus, as a matter of self preservation, we must become concerned with the environment in all its aspects. We must learn to understand the natural environment and its processes and the threats it may pose, as well as the means by which man's activities interact with the environment and tend to change it.

An important first step toward achieving these objectives is to describe the total environment in sufficient detail to permit modeling of its processes and measuring its changes on a worldwide basis. This process of observing the environment and measuring its changes is called environmental monitoring. Environmental monitoring obviously is not a new activity. For well over a hundred years regular observations of atmospheric variables have been made over wide geographic areas from surface stations, and later from balloons and other platforms. To a more limited degree, oceanic parameters have also been measured for many years. What is comparatively new is the need to measure and observe all elements of the environment over the entire globe and to acquire such data in a relatively short period of time. It is in this context that remote sensing from air and space is beginning to play such an important role in environmental monitoring, and it is this application of remote sensing which I wish to discuss with you today.

We monitor the environment for a number of different purposes. To an extent, the purpose determines how quickly we need the data and over how large an area. Of highest immediate priority in terms of protecting human life is perhaps the direct detection of imminent environmental hazards and the provision of timely warning to threatened areas. Such hazards include hurricanes, tornadoes, and other severe storms; tsunamis (seismic sea waves); floods, landslides, and unusually heavy snowfall; and other events similar in nature where timely warnings could permit taking action to save lives and protect property.

A second critical application of environmental monitoring is to the prediction of short-term environmental change: forecasting the weather, the state of the sea, the probability of earthquakes, or the occurrence of a solar flare which might produce radiation levels in the upper atmosphere hazardous to high-flying aircraft. Another type of environ-

mental change of growing importance in the preservation of environmental quality is the long-range climatic change which may be caused inadvertently by man's activities. An application to this problem that is becoming more vital every day is the monitoring of air and water pollution, both regionally and globally. Regional aspects of pollution monitoring will be discussed in more detail in the following paper.

Finally, environmental monitoring is directly related to the identification and management of the resources of the atmosphere, the oceans, lakes and rivers, and the solid Earth. These applications will be discussed in many papers presented at this workshop. The emphasis here is on applications of environmental monitoring techniques to warnings of environmental behavior and measurements of environmental quality on a global scale.

Much progress has already been made. To some extent, environmental monitoring from space is already being done operationally by the United States, using the environmental satellites of the National Oceanic and Atmospheric Administration (NOAA), and to a lesser extent by other nations. The polar-orbiting Improved Tiros Operational Satellites (ITOS) now observe the entire Earth twice a day, taking television cloud pictures and radiometric images. Beginning in 1972, these satellites will obtain daily readings globally of the vertical distribution of atmospheric temperature and humidity. Imaging resolution will be improved to approximately 1 kilometer directly below the satellites. The Geostationary Operational Environmental Satellite (GOES) system, also scheduled for operational checkout in 1972, is capable of continuous observation of the region over which it is positioned; it will produce multispectral (visual and infrared) images of most of the Western Hemisphere night and day at half-hourly intervals. Both systems will carry sensors to monitor emissions from the Sun.

With regard to observation of the solid Earth, satellites usable for obtaining accurate geodetic location of points on the surface of the Earth, even at intercontinental distances, have been flying since the launch of Echo I in 1961. While no satellites have been launched specifically to monitor the world's oceans, a start has been made using data available from meteorological satellites.

Aircraft also have been used for environmental monitoring by the United States and other countries. For example, aircraft of the United States Navy, Air Force, and the NOAA have been used for many years in locating and tracking tropical storms and monitoring other meteorological phenomena. Aircraft photography also has been used to determine snow cover over portions of the United States to assist in predictions of runoff and flood potential. Scientists of the NASA Earth Resources Survey Aircraft Program have been investigating the use of remote sensors for a variety of environmental applications, most of which will be described at this workshop. The first Earth Resources Technology Satellite (ERTS) is scheduled for flight in early 1973, as is the Earth Resources Experimental Package (EREP) on the manned Skylab satellite. Both are expected to increase our understanding of the extent to which remote sensing from space can contribute to environmental monitoring.

While I have been emphasizing the use of spacecraft and aircraft for environmental monitoring, I do not wish to minimize the importance of surface and other *in situ* sensors. Some data can be collected only *in situ*. Even where remote sensing may be the predominant mode of data acquisition, there is an axiom that holds true for all applications: Remote sensing data are useless in the absence of adequate ground truth or other *in situ* information. For example, satellite cloud photographs cannot be used to make weather forecasts unless the relationships between cloud forms and weather phenomena have been established previously. In keeping with the theme of this workshop, however, the emphasis in this paper is principally on remote sensing by satellite and aircraft as an element of the total spectrum of data acquisition required for environmental monitoring.

I would like now to review some accomplishments in environmental monitoring which have been achieved using data acquired by remote sensing from air and space, together with data from other sources.

Satellite data have powerful applications in the forecasting and warning of our most dangerous weather phenomena, the deadly and destructive hurricanes and tornadoes. Since inauguration of the operational satellite service in the United States, probably no tropical storm has gone undetected anywhere in the worldwide tropical oceans. Dis-

covery is invariably by satellite. For example, in the virtual absence of other weather reports south and east of Hawaii in the Central Pacific, many tropical storms would go undetected without satellite surveillance, and a violent storm could strike the islands without warning as has happened in the past. Figure 1 shows an example. In late August 1970, Hurricanes Maggie and Lorraine were east of Hawaii and were thought to be weakening. But in the satellite picture for August 25 the cloud structure of Maggie, the nearer storm, showed she was still intense. On the basis of this information, the forecaster called for much heavier precipitation than he otherwise would have. The next day Maggie brushed by the island of Hawaii and produced very heavy rainfall. Lorraine, on the other hand, was correctly forecast from the satellite pictures to be no threat to the islands.

Figure 2 is a photograph of an approaching tornado—the most dangerous of all storms. We do not yet understand how to predict the occurrence of tornadoes with any degree of certainty. On the other hand, the nearly continuous cloud photographs available from geosynchronous satellites, such as the sequence from ATS III shown in figure 3, permit quick identification of regions in which such severe storms might occur. Ground-based radar, another form of remote sensing, because of its current availability to the forecaster, is of special value when tornadoes are forming. Figure 4 shows a sequence of radar photographs made in the vicinity of Lubbock on the same day as the satellite photos of figure 3.

While there are a number of applications of remote sensing techniques to environmental threats and disasters, of which these two examples are representative, there are other types of disasters (earthquakes, for example) for which we have not yet developed warning techniques. It is hoped that, as we gain experience with remote sensing, these techniques will be developed.

In the area of short-term prediction of environmental events, there has been significant application of environmental monitoring by remote sensing techniques. Figure 5 is a computer-prepared mosaic of the Northern Hemisphere on September 13, 1969, which shows the distribution of clouds for the entire region. This type of mosaic is now used routinely

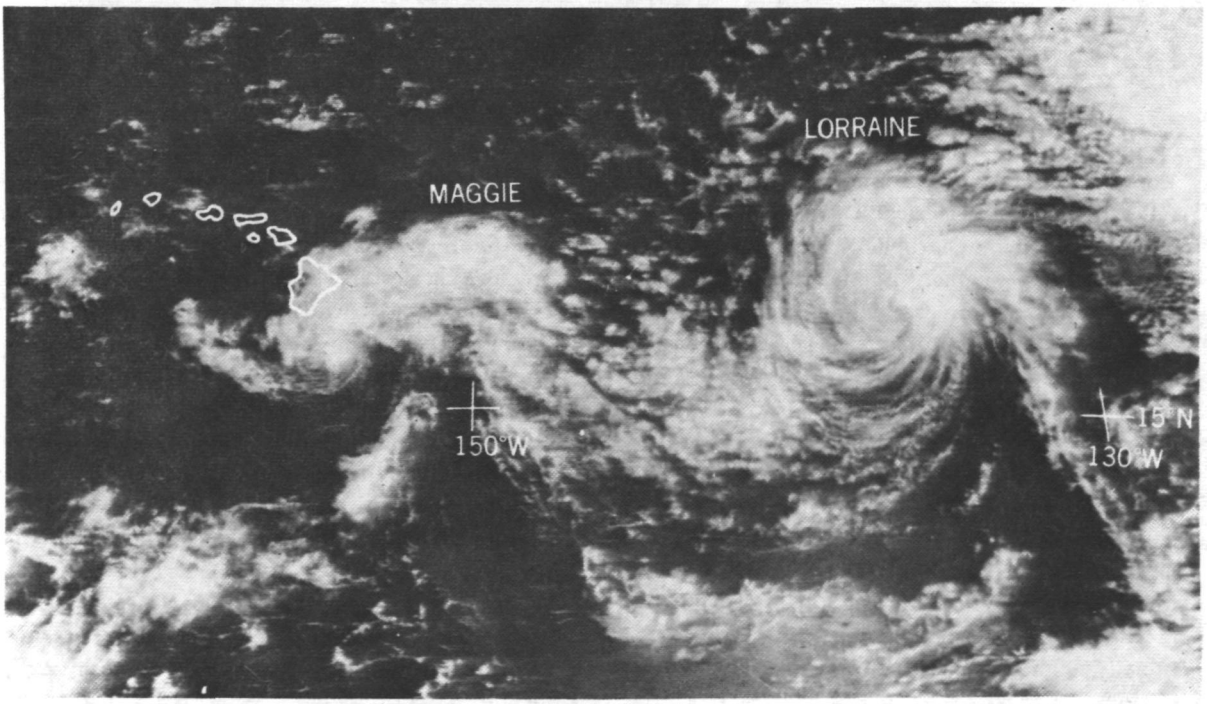

FIGURE 1. Hurricanes Maggie and Lorraine east of Hawaii, August 25, 1970.

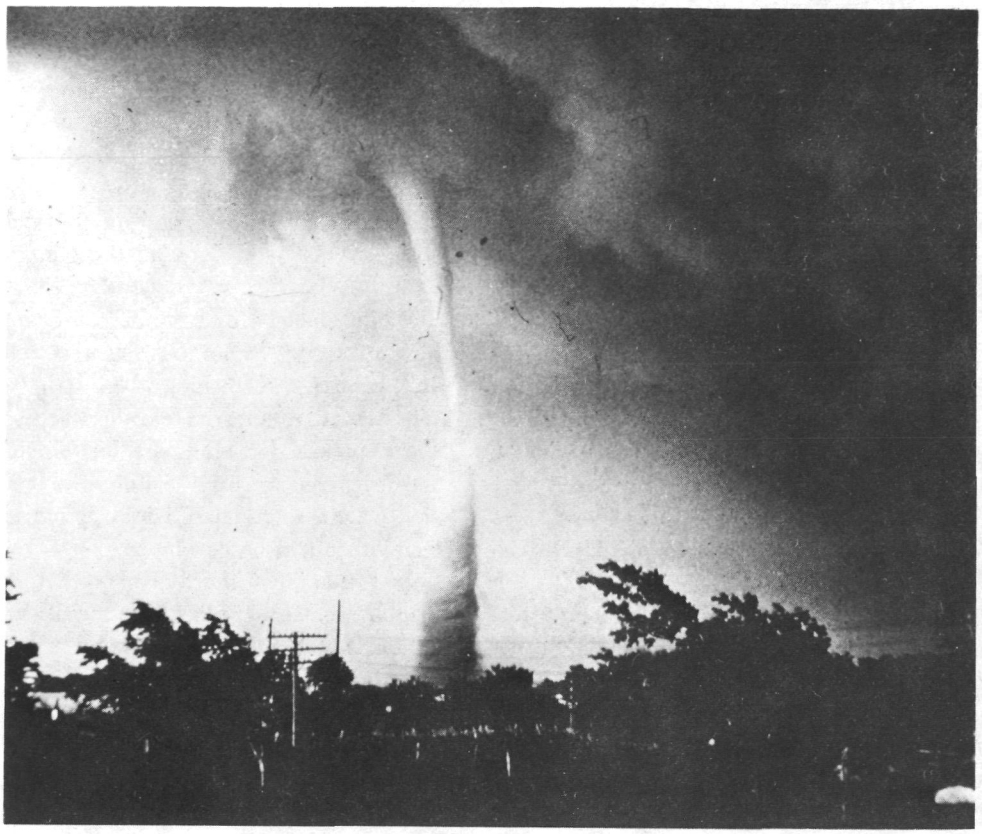

FIGURE 2. The most dangerous and unpredictable of all storms, a tornado approaches with devastating speed.

by the National Meteorological Center at Suitland, Maryland in the preparation of Northern Hemisphere and North American weather analyses.

While cloud photographs are of great value in portraying the weather situation, the meteorologist cannot prepare a forecast without quantitative data on the state of the atmosphere. A beginning has been made in obtaining quantitative data from satellite-borne remote sensors.

Figure 6 compares remote sensing data taken from the satellite infrared spectrometer (SIRS) flown on Nimbus III with conventional sounding data taken from balloonborne radiosondes the same day. SIRS uses infrared radiance at a variety of wavelengths to determine the vertical temperature profile of the atmosphere. Agreement with conventionally obtained observation is excellent at this station.

Although such infrared observations from a satellite can be made only above the cloudtop level, except in cloud-free areas, the data permit the construction of a number of useful products. For example, figure 6 also shows a 300-millibar constant-pressure chart prepared entirely from satellite soundings as compared with the chart for the same time period prepared from conventional sounding data. Such charts are used in the preparation of weather forecasts.

Knowledge of the global sea surface temperature is an essential type of data for improving long-range weather forecasts because it contributes to knowledge of the total energy balance of the ocean-atmosphere system. Figure 7 represents the temperature distribution in the Pacific Ocean as determined by satellite infrared sensors on Nimbus II. This type of information is currently available on an experimental basis in cloud-free areas over the entire globe.

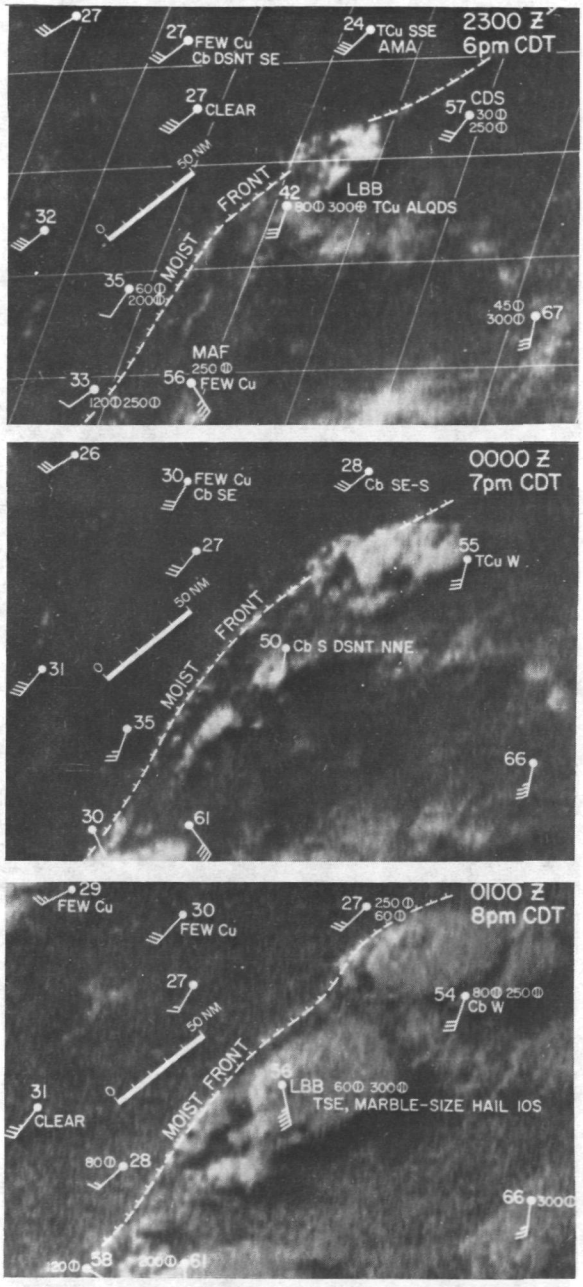

FIGURE 3. Series of photographs from ATS III, taken at 1-hour intervals on May 11, 1970, shows tornado activity in the vicinity of Lubbock, Texas.

Knowledge of the presence of ice and snow over land and sea is important both for weather forecasting and for predicting the amount of water which will be available in rivers and lakes following runoff. Such information is also of importance in predicting hazardous floods. Figure 8 is a satellite photographic mosaic for March 10, 1970, showing clouds usually visible in a satellite photograph. By a special process, a composite mosaic (figure 9) showing only the minimum brightness that appeared over an area during 5 successive days is produced. In this composite all but the most persistent cloudiness has been removed, and the remaining bright areas represent ice and snow. This type of product is now being prepared regularly by the National Environmental Satellite Service.

Interest in environmental prediction extends to regions other than the atmosphere and oceans. For example, sunspots, solar flares, and other types of disturbances may affect communications, space and aircraft operations, and even electric power networks on the Earth's surface, so it is necessary to predict such events and their effects on other regions of the environment as accurately as possible. The Space Disturbance Forecast Center of the NOAA makes such predictions, making extensive use of satellite data. Figure 10 shows schematically how this function is performed. At present, the principal sources of satellite data to the center are the NASA ATS satellites and the NOAA satellites. Beginning in early 1973, the GOES satellites will become an important source of data, and other sources will be added in future years.

We come now to an application area of very great importance, even though the time dependence of the data is less critical. The application I refer to is that of detecting climatic change, whether attributable to natural causes or to changes connected with weather as we normally think of it, but also to changes or trends in any aspect of environmental quality. This is currently an area of very great concern in the United States. In response to this concern, NOAA has recently prepared a geophysical monitoring plan for climatic change. Here we are concerned, for example, with trends in average temperatures and rainfall, the amount of carbon dioxide in the atmosphere, pollution of the atmosphere by harmful particulate and gaseous matter, water pollution, and land use.

Very accurate point observations are made at key climatic reference stations, such as the one at the top of Mauna Loa on the island of Hawaii (figure 11). Such stations, located in regions generally free from local pollution sources, provide reference

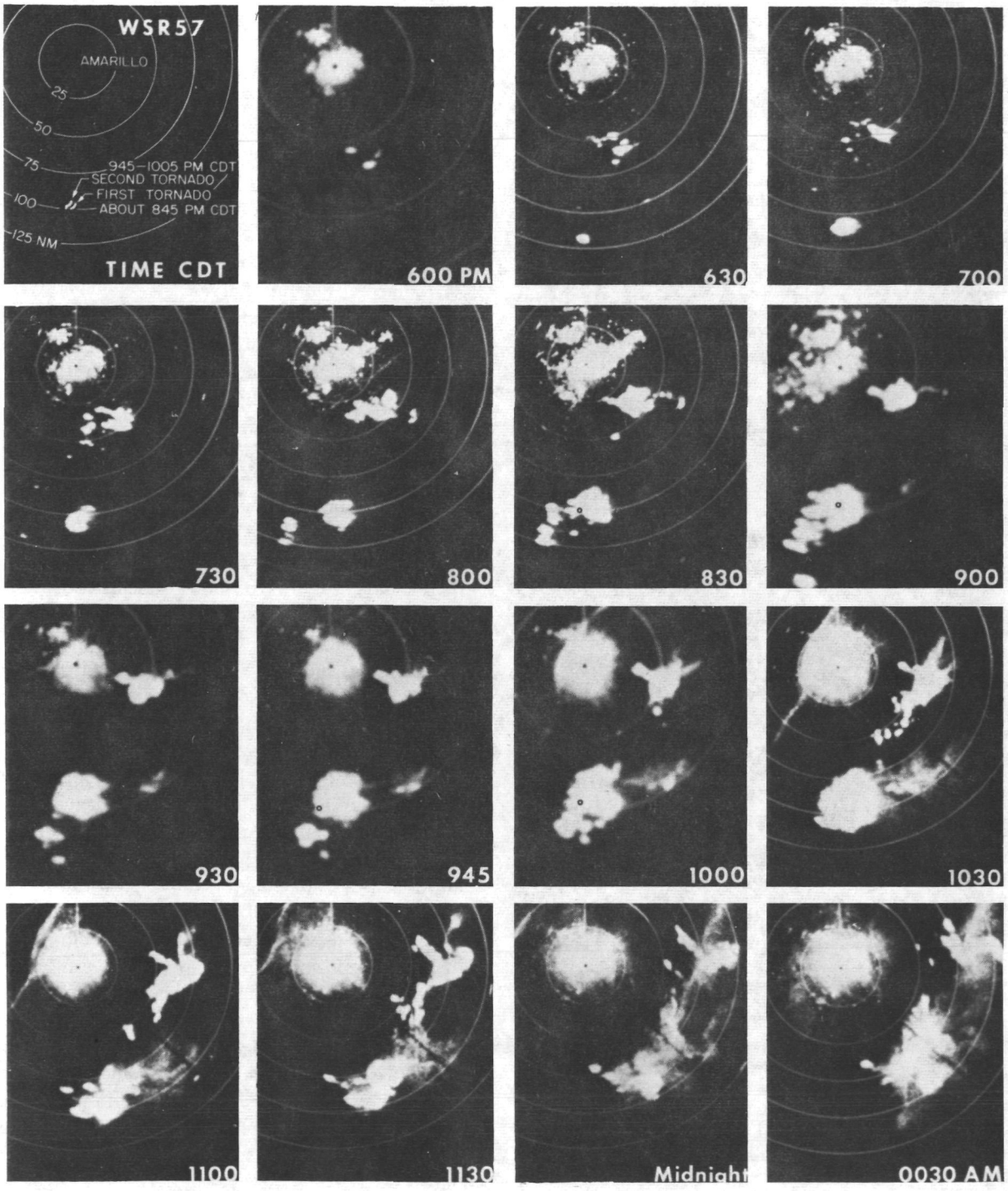

FIGURE 4. Series of ground-based radar photos shows same tornado activity near Lubbock on May 11, 1970.

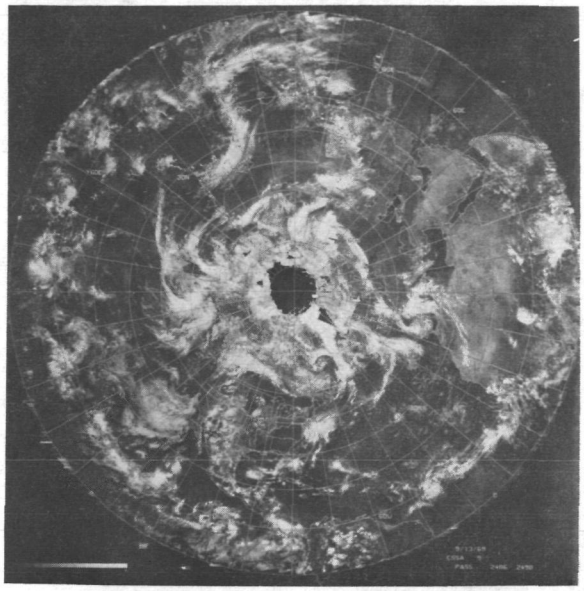

FIGURE 5. Cloud distribution over entire Northern Hemisphere is shown in this computer-prepared photomosaic.

data to which other observations may be related. Byrd Station in Antarctica is another key reference station.

Since a large percentage of the world's fresh water is stored in the form of snow and ice on the Antarctic Continent, and since approximately 65 percent of the net blackbody radiation needed to maintain the Earth's equilibrium temperature is emitted from that continent, temperature and precipitation trends in this region are critical to world climate. To further this knowledge, deep holes have been drilled in the glacial ice at Byrd Station and at Camp Century in Greenland. Examination of the various layers of ice has revealed the climatic history of the Earth for approximately the past 40 000 years, providing a reference for present trends. Figure 12 is a cloud-free photograph of the Antarctic Continent made using the composite minimum brightness technique.

The significant value of satellite remote sensing observations is that they provide a means for relatively reliable interpolation between surface climatic reference stations. For example, figure 13 represents a 30-day brightness average from mid-July to mid-August 1969 for the Northern Hemisphere; this is an indication of the mean cloud cover and precipitation for the month. Figure 14 is a 90-day average during the winter of 1970–71.

Turning now to another part of the environment, the coastal zones of the continents are an important source of both mineral and biological resources. But they are very susceptible both to pollution and to misuse by man. The so-called wetlands or marshy areas in the vicinity of the coast are very important ecologically. Figure 15 shows a black-and-white print of a false-color infrared photograph (top) and a print of the infrared channel only (bottom) of the coastal area of the State of Georgia in the southeast part of the United States. This type of photography permits clear identification of the wetlands, as can be seen in the upper photograph. Repetitive coverage permits monitoring the quality of this portion of the environment and rapid detection of any significant change.

These examples indicate what has been done and can be done with current technology for environmental monitoring. We have only begun to use remote sensing for this purpose; most applications are still in the planning stage. Because of the importance to all of us of the future of the global environment, I would like now to talk a bit about the future and what it may bring in the way of tools for environmental monitoring. I would also like to speculate a bit about ways in which we may work together in the future to insure a better environment for all mankind.

I have mentioned the value of satellite remote sensing for interpolation between surface observations. This application should increase in the future as we find means to measure more variables by remote sensing. For example, the ability to obtain global temperature and humidity soundings daily, even from remote areas where there are no observers present, will greatly contribute to our knowledge of world climatology.

The acquisition and storing of data, while of great value in itself, is not itself sufficient to solve all environmental problems. A very high-priority objective must be to develop a capability to model the total environment and its interactions. Only with such models can we determine the consequences of man's activities. The ability to observe and collect data continuously over the entire globe will inevitably make a major contribution to meeting this objective.

Already we are modeling the Earth's atmosphere, at least to some extent; these models are the

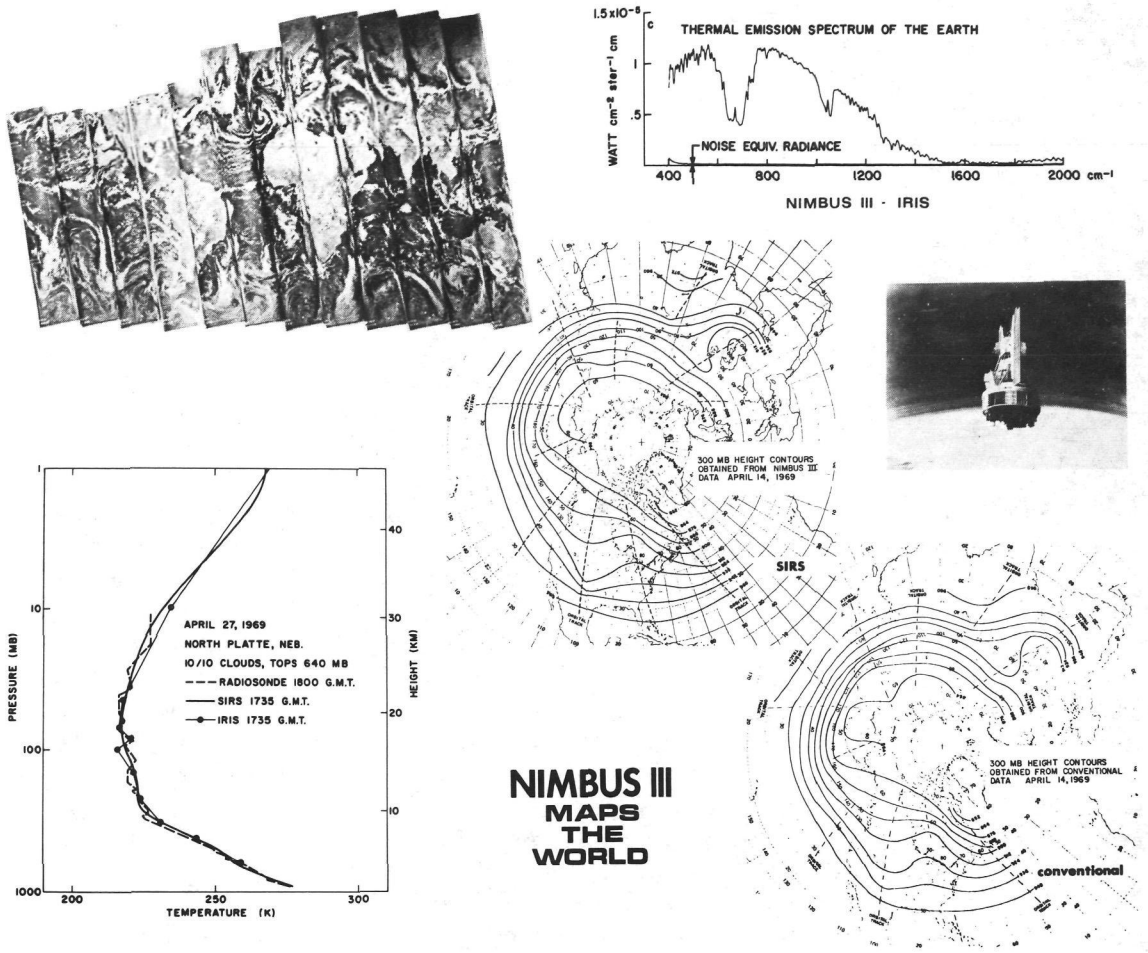

FIGURE 6. Satellite infrared spectrometer (SIRS) data compares closely with conventional sounding data.

basis of long-range weather forecasts. We must now extend this concept to include the total spectrum of the environment, from the input of solar energy through the dynamic processes of the upper and lower atmosphere to interactions with the turbulent oceans and the solid Earth beneath. Our models must be sufficiently accurate to predict the long-term effects of collective human actions such as pollution, as well as individual actions such as weather modification experiments. Within the next 10 years or so, we should have the capability to observe virtually the entire physical environment and its dynamic changes. Continuous global observations will enable us to complete the modeling necessary for accurate prediction.

Other regional and global measurements will be needed to monitor environmental quality and prevent its degradation. We will need to identify certain key indices of quality and attempt to relate these indices to parameters which may be observed from air and space. I should like now to speculate as to what some of these indices might be and how data for their monitoring might be obtained.

What are the significant indices of environmental quality? In the absence of adequate environmental models, this question is difficult to answer. We are not sure we understand all of the parameters or the functional relationships between these parameters and environmental quality. Nonetheless, it may be useful to suggest a list as a starting point for discussion.

First of all, we do not understand by what means

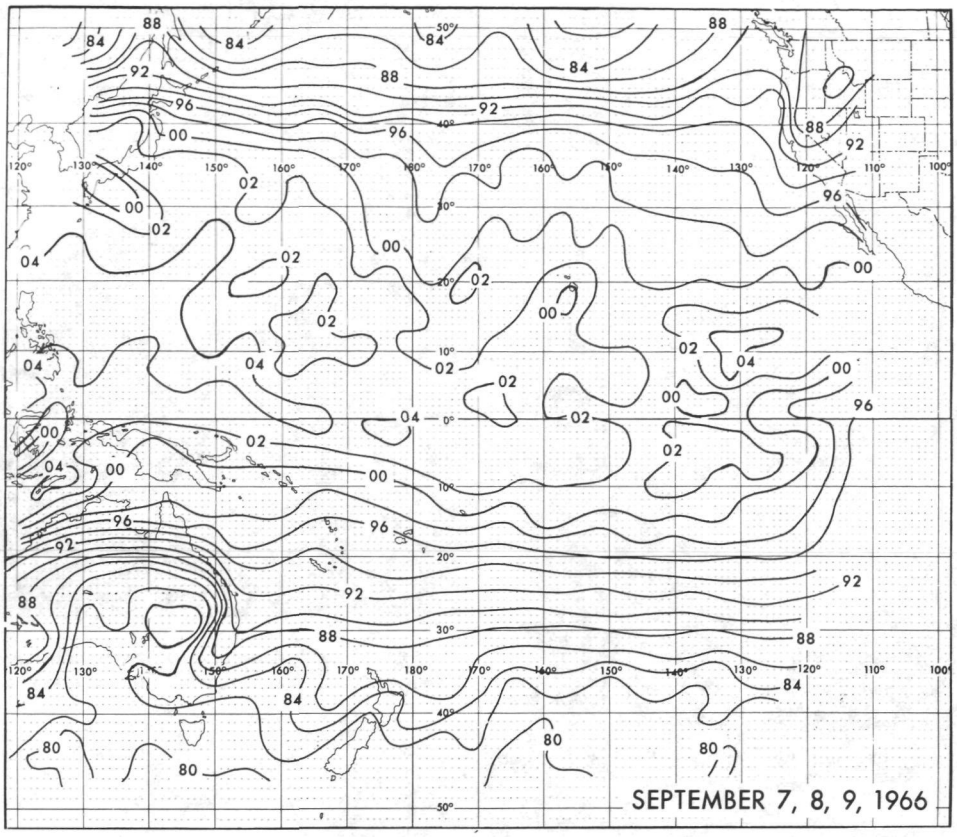

FIGURE 7. Pacific Ocean temperature distribution prepared from Nimbus 2 IR sensor data.

events on the Sun affect the environment here on Earth. At the same time, it would be foolish to assume at this point that solar events do not affect environmental events, at least in the upper atmosphere. We are already collecting data, much of it by satellite, concerning sunspots, solar flares, solar particle emissions, and other significant events. In each case, indices of activity can be established. Similarly, we measure electron and ion densities in the upper atmosphere and fluctuations in the Earth's magnetic field.

In the lower atmosphere, there are undoubtedly a number of parameters related to environmental quality. These parameters in general have significance both regionally and globally and hence must be indexed as a function of time, place, and altitude. Such parameters include the vertical distribution of atmospheric temperature, humidity, density, cloud cover, and precipitation, all of which are conventional climatic parameters. Surface temperature is another important parameter which must be indexed, and the mean temperature of the Earth is almost certainly an environmental quality factor of great importance.

With particular regard to air pollution, several additional parameters might be measured. These include, in addition to the climatic variables already identified, such factors as turbidity, particulate and gaseous contaminants, and the height of the mixing layer. As an example of how an index might be derived for one of these parameters by remote sensing, one might install high-intensity monochromatic light sources at key cities around the world for viewing by multispectral sensors. Whenever cloud-free conditions exist, both absorption and frequency shift could be observed, and net particulate contamination as well as particle size distribution might be deduced. Active laser systems carried on a satellite might make possible the measurement by Raman scattering of gaseous contaminants such as NO and NO_2 for the same regions. With this type of data available, it should be possible to develop

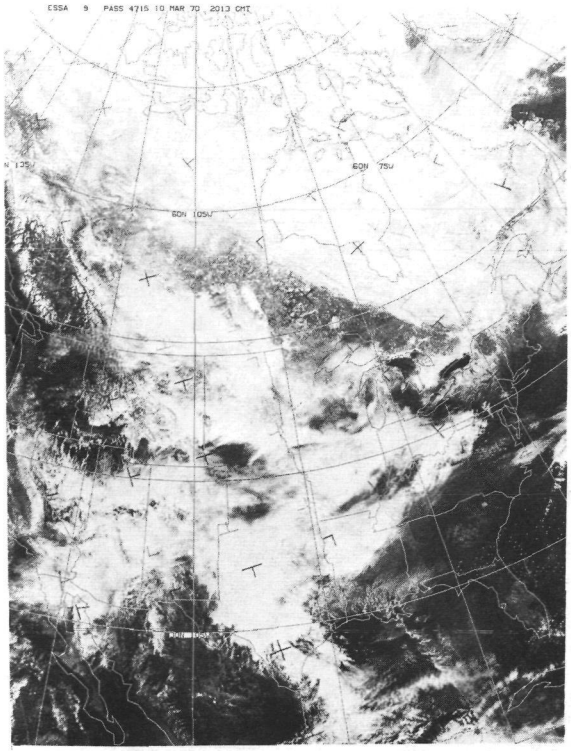

FIGURE 8. Satellite photomosaic showing entire visible cloud cover.

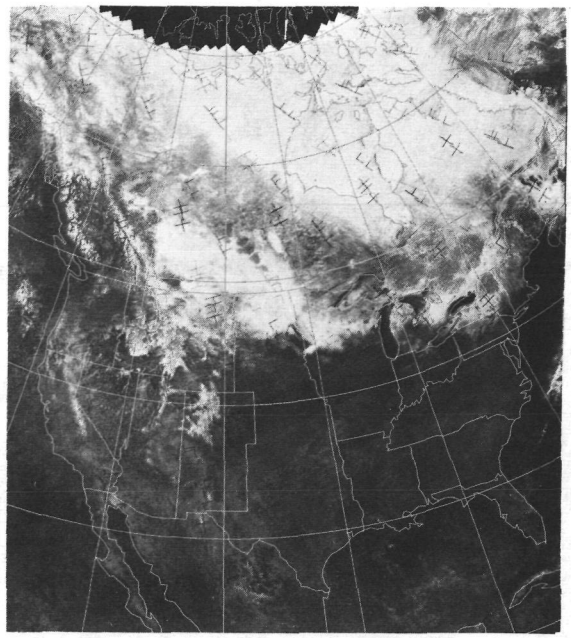

FIGURE 9. Five-day composite minimum-brightness mosaic removes most clouds, leaving snow and ice clearly visible.

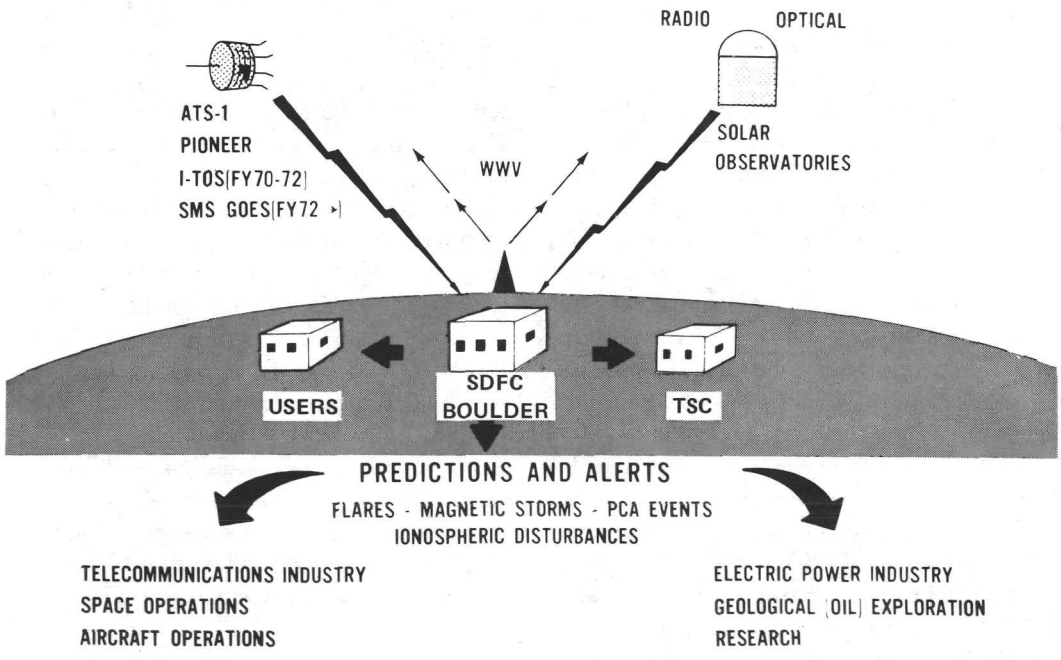

FIGURE 10. Schematic diagram of solar forecasting activities.

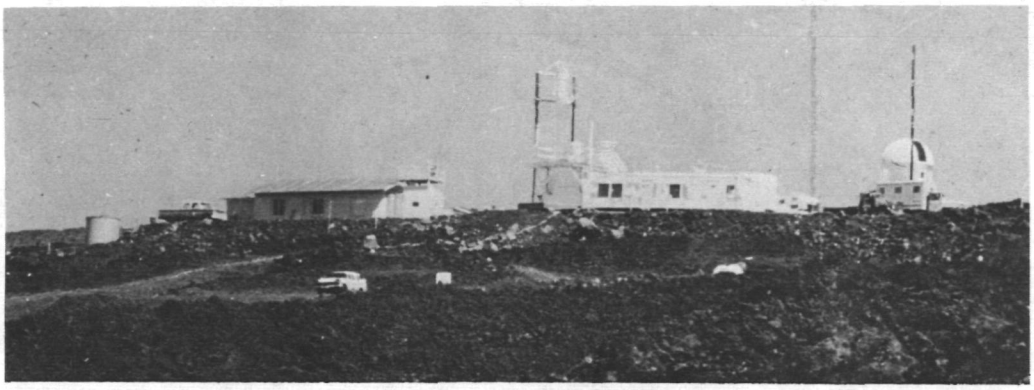

FIGURE 11. Mauna Loa climatic reference station.

an index of pollution, based on monthly averages, for each of the cities with the high-intensity light sources. These local index numbers could be combined in some form to produce regional and national indices, and finally a global index of pollution might be computed at regular intervals.

For the oceans, lakes, and coastal zones, we will be interested in other parameters. The positions and motions of large ocean currents have major effects upon climate throughout the world. General circulations of the oceans should be deducible from the sea slope produced by gravitational anomolies, measurement of which may be obtainable in the future from low-altitude drag-free satellites. Meteorological observations and measurements of sea conditions will give some indication of probable change in position of major currents, as well as the behavior of smaller currents. Sea surface temperature is an important parameter related to ocean quality, as are chlorophyll content and the presence of algae, all of which may someday be detectable with satellite sensors. Sea ice, another factor affecting ocean quality, can be observed by remote sensing.

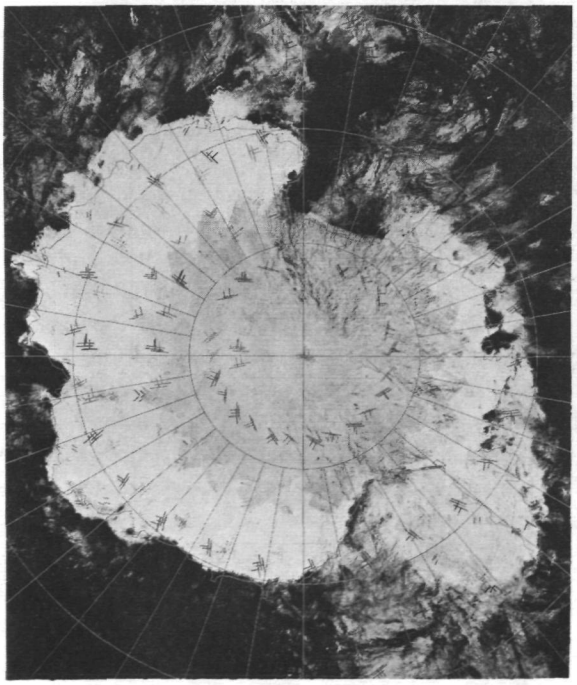

FIGURE 12. Five-day composite minimum-brightness photo of Antarctica.

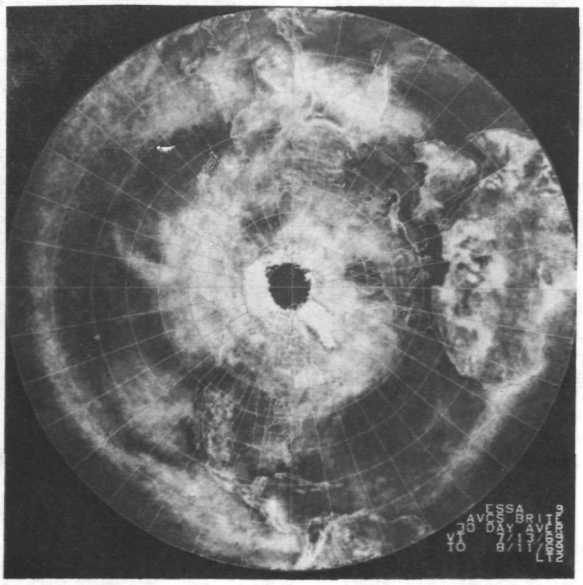

FIGURE 13. Thirty-day average-brightness composite shows mean cloud cover and precipitation over Northern Hemisphere.

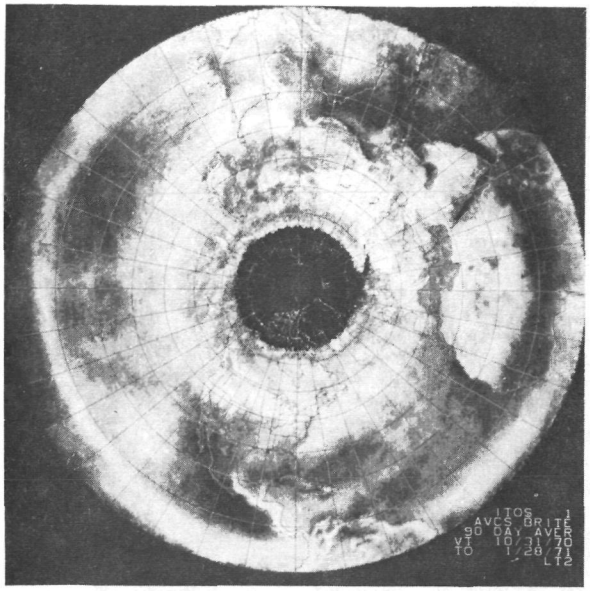

FIGURE 14. Ninety-day average-brightness composite shows mean cloud cover and precipitation for entire season.

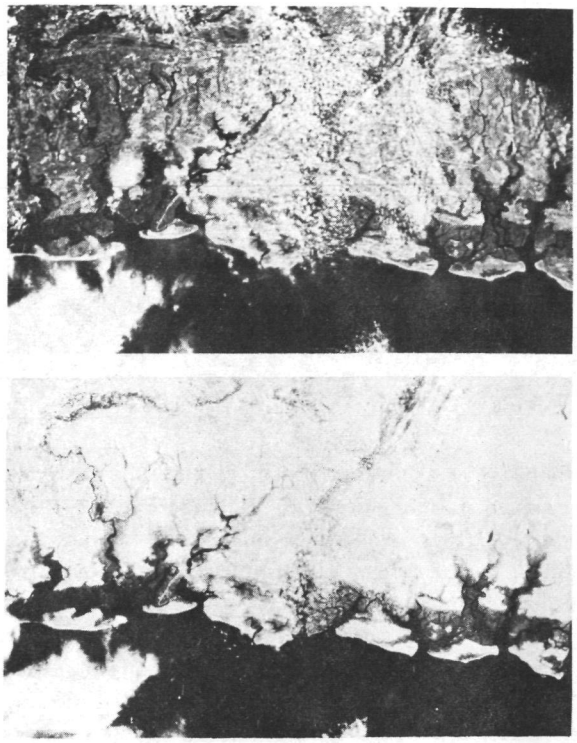

FIGURE 15. Infrared photoimagery identifies wetlands on Georgia coast in southeastern U.S.

Over the land areas of the world, another set of parameters will be of importance. We will be concerned with ice and snow cover; soil moisture and types of soils; nature, extent, and health of vegetative cover; and land use practices, all of which affect environmental quality and could be measured by aircraft and satellite remote sensors. The Earth's magnetic field may prove to play a significant role in environmental quality. It has been suggested, for example, that the Earth's magnetic field may be slowly reversing, in which case it would pass through zero at some future time. Since in the absence of a magnetic field solar particles would not be deflected, a dangerous rise in cosmic radiation harmful to human beings and other animals might then take place at the Earth's surface.

Finally, as has been suggested earlier, the irregular motion of the poles as the Earth rotates may bear an important relationship to major earthquakes and other seismic events.

The list I have given is far from complete, but it does suggest the great variety of measurements which may be necessary if we are to fully understand our environment and prevent its degradation. There seems little question that remote sensing from space and from aircraft is destined to play a major role in our attempt to preserve the global environment for future generations. Since we are all revolving around the same Sun together and the environment is global, I have no doubt that the problem of surviving on Earth can be approached only through a common effort of all nations working together. In the next few decades we may well face the greatest challenge to survival in the history of the human race. With the aid of remote sensing from space and from aircraft, let us dedicate ourselves to meeting that challenge.